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AFCI Transmutation Fuel Processes And By-Products Interim Report

Eric L. Shaber

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Interim Report

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Idaho National Engineering and Environmental Laboratory
Idaho Falls, Idaho 83415

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TABLES

ACRONYMS

AFCI	Advanced Fuel Cycle Initiative
DOE	Department of Energy
FDWG	Fuel Development Working Group
FFF	Fuel Fabrication Facility
GFR	Gas Fast Reactor
LTS	lead test assembly
LWR	light-water reactor
NMCA	Nuclear Materials Control and Accountability
NRC	Nuclear Regulatory Commission
QC	Quality Control
SFTF	Spent Fuel Treatment Facility
TRISO	tri-isotopic (fuel)

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1. INTRODUCTION

1.1 Background

The Advanced Fuel Cycle Initiative (AFCI) has two missions[1]:

- Develop and demonstrate advanced nuclear energy systems
- Develop and demonstrate technologies for stable, long term, advanced fuel cycles.

The AFCI chartered the Fuel Development Working Group (FDWG) to provide proliferation – resistant fuels for use in advanced fuel cycles for both light-water reactors (LWRs) and for the next generation of nuclear power and transmutation systems.

LWR transmuter fuels are constrained by the physical configuration and power density limitations of the LWR industry. The focus of efforts on fuels is the development of recycle fuels that incorporate proliferation resistant features and reduce the quantity of high-level waste (HLW) that must be stored in a repository. Generation IV reactor transmuter fuels do not have the limitations of use in an LWR fuel geometry and expand on the LWR type fuel requirements for to maximize the transmutation performance and significantly reduce the long-term toxicity and decay heat of the fuel. Both fuels will contain isotopes that need to be transmuted to reduce repository requirements and make the fuels undesirable for nuclear proliferation. These isotopes include Pu, Np, Am, and probably Cm, in addition to U.

At specialized national laboratory facilities small quantities of these isotopes are being fabricated into fuel for irradiation tests. Fabrication of larger quantities of such fuels is currently prohibitive because of the radiation exposures involved. Production of LWR lead test assemblies (LTA's) or reactor core loads will require new pilot facilities or construction of a production Fuel Fabrication Facility (FFF) designed to handle the isotopes in large quantities.

The specification of fabrication facilities capable of producing transmutation fuels dictates the need for detailed process flow information. Full definition of the materials that will need to be handled as feed material inputs, scrap, and by-product wastes is required. The feed material for transmutation fuel fabrication will need to come from the Spent Fuel Treatment Facility (SFTF). The SFTF would also represent the only capability for recycle of transmutation isotope fuel scrap materials generated during fuel fabrication. Therefore, interface with the SFTF is an essential component in defining and finalizing a fuel fabrication process.

1.2 Objectives

This interim report provides the initial process flow, scrap recycle flow, and characterization flow information for five fuel forms currently being considered for fabrication and use as transmutation fuels. It will be updated when new information is available. The process definition information provided here is intended to reflect processes used in a pilot or production scale fuel manufacturing operation. However, the process sequence data has been extrapolated from current developmental practices that may require further refinement for production scale-up. All process information must be considered preliminary at this time as the fuel forms are still under development and adjustments in the quantities of individual isotopes in the fuels could significantly affect processing methodology.

2. FUEL PROCESSES

2.1 Flow Diagram Construction

One of the first steps in process definition is the identification of the unit processes and sequential operations required to manufacture a fuel product. Such process definition is typically done in a logic diagram format as an aid to ensure that processing steps are not missed or inputs or outputs are not accounted for.

Process information was obtained from the national laboratory developers for five transmutation fuel types being considered for use: mixed oxide, mixed nitride, metal alloy, tri-isotopic (TRISO), and dispersion. Each fabrication process flow sequence, with an associated scrap recycle sequence and characterization/quality control test sequence, was diagramed to capture the essential components of each process. Where the needed feed material for fuel fabrication differs from the output product currently defined by the SFTF, feed material form adjustments have been added to the front end of the fabrication flow diagrams.

2.2 Mixed Oxide Transmutation Fuel

2.2.1 Mixed Oxide Process Flow

The mixed oxide transmutation fuel is a pellet fuel intended for direct replacement of oxide fuel pellets in an LWR reactor. It is similar to the "Commercial MOX" fuel being fabricated for Pu recycle except that the fuel contains Np, Am, and potentially Cm, in addition to Pu. The process flow diagram for fabricating this fuel is provided as Attachment 1. Although the flow diagram shown is specifically for an LWR-type fuel pellet, similar processing methods may be employed with different isotopic compositions to manufacture a Generation IV version of mixed oxide fuel.

2.2.2 Mixed Oxide Material Recovery Flow

Mixed oxide fuel pellet fabrication success and reactor performance are tied to the sintered characteristics of the fuel pellets. LWR fuel fabrication experience has shown that specific fractions of recycle oxide powders blended with specific fractions of first pass powders provide the optimum sintered characteristics for LWR fuel. Such process optimization understandings, however, may not be applicable to mixed oxide fabrication involving multiple isotopes where oxide stoichiometry, sintering conditions, and powder morphology may be major factors in achieving acceptable process results.

Scrap recycle may be required from several unit processes used in mixed oxide fabrication, but the scrap recycle streams (shown in orange on the flow diagram [see Attachment 1]) are of primary concern because of the additional unit processes involved to return the material to a usable condition. A preliminary estimate of the material recovery processes needed for mixed oxide scrap recycle are shown in the flow diagram provided as Attachment 2. There are three potential exits from the material recovery process sequence: return to the fabrication process, return to the SFTF for additional separations processing, or disposal as a waste product. The characterizations performed for material recovery are shown on the characterization flow sheet provided as Attachment 3.

The size of the material recovery unit processes will be a function of the expected reject rates from the fabrication unit processes. Estimation of reject rates and quantification of the materials that would move through the material recovery processes will be the subject of future work.

2.2.3 Mixed Oxide Characterization Flow

Statistical samples of intermediate products are removed from the mixed oxide process line for analysis. The quality control characterization tests performed on these materials are required to determine if the product can continue through the process or will be relegated to a scrap recycle sequence. The steps used to analyze mixed oxide fuel are identified on the characterization process flow diagram (Attachment 3). Each characterization sequence is identified with a letter corresponding to the inspection block on the process flow or material recovery flow diagrams (Attachments 1 and 2, respectively). Although some characterization tests are non-destructive, most sample material does not get returned to the process line but is held at least until final certification of the fuel batch represented by the sample.

2.3 Mixed Nitride Transmutation Fuel

2.3.1 Mixed Nitride Process Flow

Although less developed, the nitride fuel process is intended to achieve the same goals as the mixed oxide process. The nitrides have a potential benefit over the oxides from the viewpoint of thermal conductivity that may make them more attractive for AFCI transmutation applications. The current process flow sheet for nitride transmutation fuel is provided as Attachment 4. The process starts with oxide feed materials, and the conversion to nitride is an integral part of the processing because the potential exists for powder oxidation if nitride feed materials were employed from SFTF.

2.3.2 Mixed Nitride Material Recovery Flow

The recovery of scrap materials for the nitride process is quite similar to the recovery processes for oxide fabrication with the addition of a burn process to modify the form of the nitride scrap back to an oxide. The recovery process flow diagram is provided as Attachment 5. Characterization requirements for material recovery are letter coded and found on the characterization flow sheet (Attachment 3).

2.3.3 Mixed Nitride Characterization Flow

The characterization of nitride fuel is sufficiently similar to that of mixed oxide that the same diagram is used for both (see Attachment 3). Each Quality Control (QC) check point in the mixed nitride process is coded with a letter corresponding to the appropriate box on the characterization flow sheet.

2.4 Metal Transmutation Fuel

2.4.1 Metal Process Flow

Metal fuels have a long history of reactor usage and would provide distinct advantages in process simplicity if metallic feed materials can be provided by the SFTF. Metal alloy fuels are being considered primarily as inserts for isotope transmutation. In manufacturing, the specific isotopes of interest are combined in the desired quantities and alloyed with Zr metal in an arc melt sequence. This allows a wide variety of compositions while maintaining alloy corrosion resistance. The current process provides a Na-bonded and clad fuel element that is then used as the fuel for insertion in an LWR-type fuel assembly.

Current development and irradiation testing efforts are using alloys in the as-cast condition. The flow diagram provided as Attachment 6 currently assumes that larger castings would be made in a production environment and that final pin diameters would be achieved by extrusion, forging, or rolling. Although the mechanical work is not required to achieve fuel properties, it is considered necessary to achieve adequate process throughput.

2.4.2 Metal Recovery Process Flow

The metallic fuel process involves arc melting of fuel feed materials in a vacuum which will volatilize and/or separate impurities from prior reduction processing. A small recovery line may be needed to recycle feedstock isotopes that do not meet composition or impurity starting requirements, and to recycle any fuel elements that are unsuccessfully loaded. These recovery processes are shown on the main process flow diagram (see Attachment 6) in orange.

2.4.3 Metal Characterization Process Flow

The quality control characterization processes used for metallic fuel are straightforward and are provided as Attachment 7.

2.5 TRISO Transmutation Fuel

2.5.1 TRISO Process Flow

TRISO fuel is a ceramic particle fuel with a ceramic isotope kernel surrounded by multiple isotropic coatings. One coating, either SiC or ZrC, provides a barrier to fission product release as part of the fuel particle. The fuel does not use any metal cladding. TRISO fuel is designed for gas reactors that are being considered in the Generation IV Reactor program. From the AFCI viewpoint, they represent a Generation IV fuel type only. TRISO fuel has a unique advantage in that each microscopic fuel particle has its own individual fission product barrier. This eliminates the issue of reactor shutdown due to a fuel cladding failure event. The performance of TRISO fuel should be statistically predictable from the fabrication QC test data.

The downside to TRISO fuel is the processing complexity involved, as can be noted in the process flow sheet provided as Attachment 8. The complexity may prove to be a major issue for processing transmutation isotopes that require remote operations. The development of the TRISO process is still in progress, and as the processes mature, simplification methods should become more apparent and the feasibility of remote fabrication should improve. At this time, the feasibility of processing transmutation isotopes along with U is being assumed. Issues with high-temperature processing of Am are expected, but should be possible to overcome.

2.5.2 TRISO Scrap Recovery Flow

The complexity of the TRISO fuel fabrication process is not reflected in scrap recovery. Fuel particles from essentially any location in the process can be crushed, burned, leached, dried and returned to the start of the process sequence. These scrap recovery processes are shown on the main process flow sheet (Attachment 8).

2.5.3 TRISO Fuel Characterization Process Flow

The current flow sheet for characterization of TRISO fuel is complex and reflects the current developmental nature of the process (see Attachment 9). As with the main process flow, simplification of the characterization sequences required for this fuel form would be needed to successfully perform transmutation fuel characterization in a remote environment.

2.6 GFR Dispersion Transmutation Fuel

2.6.1 GFR Dispersion Fuel Process Flow

Gas Fast Reactor (GFR) dispersion fuel is a new fuel type currently under development that would be used for Generation IV applications only. The fuel has some similarity to TRISO fuel in that it is a coated particle fuel with an individual fission product barrier layer. The major differences relate to the particle coatings and compact fabrication that encapsulate the isotopes in various morphologies of SiC. A variant of dispersion fuel is also being considered that would have coatings of ZrC rather than SiC, but this fuel is only a concept at this time. An estimate of the process flow for GFR dispersion fuel is provided as Attachment 10.

2.6.2 GFR Dispersion Fuel Scrap Recovery Process Flow

The recovery of scrap generated in the GFR dispersion fuel process appears to be straightforward and very similar to that for TRISO fuel. It is shown on the GFR dispersion Fuel process flow diagram (Attachment 10).

2.6.3 GFR Dispersion Fuel Characterization Process Flow

At this stage in the development process, the actual characterization requirements for GFR dispersion fuel are still being developed. A conceptual characterization flow sheet was generated for these processes based on the types of characterization information considered necessary for TRISO fuel. This flow sheet is provided as Attachment 11.

2.7 Summary of Process Inputs and By-Products

The process input and by-product materials that are not part of the fuel feed isotopes or final fuel product are summarized in Table 1 for each process considered. Non-radioactive items such as fuel cladding tubes are assumed to be provided to the process in the finished condition, ready to use. This listing does not attempt to identify the miscellaneous waste products such as duct tape, kim wipes, latex gloves, shoe covers, lab coats, etc. that would be associated with any fuel manufacturing operation.

Table 1: Summary of Process Inputs and By-Products

Fuel Process	Inputs	By-Products
Mixed Oxide Fuel		
Fabrication	Polyethylene Glycol Zinc Stearate Argon + 6% Hydrogen SiC Grinding Media Hydrofluoroether Fuel cladding tubes End fittings Springs Weld filler metal Tungsten electrodes	HEPA Filters Zinc Oxide

Recovery	Nitric Acid Hexane or Kerosene Tributylphosphate	HEPA Filters Zinc Oxide Liquid Filter Press Media Cladding Hulls Zirconium Oxide Powder TRU Waste Solids
Characterization	Hydrochloric Acid Ethanol Silicon Carbide Hydrofluoroether Diamond Mercury He Gamma Radiation Source Sodium Hydroxide	HEPA Filters Process Water (Contaminated) Mercury Contaminated Pellets
Mixed Nitride Fuel		
Fabrication	Polyethylene Glycol Zinc Stearate Graphite Argon Nitrogen + 6% Hydrogen SiC Grinding Media Hydrofluoroether Fuel cladding tubes End fittings Springs Weld filler metal Tungsten electrodes	HEPA Filters Zinc Nitride
Recovery	Nitric Acid Hexane or Kerosene Tributylphosphate	HEPA Filters Zinc Oxide Liquid Filter Press Media Cladding Hulls Zirconium Oxide Powder TRU Waste Solids
Characterization	Hydrochloric Acid Ethanol Silicon Carbide Hydrofluoroether Diamond Mercury He Gamma Radiation Source Sodium Hydroxide	HEPA Filters Process Water (Contaminated) Mercury Contaminated Pellets

Metal Fuel		
Fabrication	Hydrofluoric Acid Magnesium Argon + Helium Zirconium Quartz tubes Hydrofluoroether Graphite Fuel Element Tubes Sodium Thoria Electrodes Fuel Assembly Tubes Acetone Alcohol	HEPA Filters Fluorination Condensate Water Magnesium Fluoride Arc Melt Furnace Slag
Recovery	None	HEPA Filters
Characterization	Hydrochloric Acid Sodium Hydroxide He Gamma Radiation Source	HEPA Filters Process Water (Contaminated)
TRISO Fuel		
Fabrication	Nitric Acid Process Water Urea Tamol Hexamethylenetetramine Carbon Black Trichloroethylene Sodium Hydroxide Hydrogen Argon Carbon Monoxide Propylene Gas Acetylene Gas Methyltrichlorosilane Graphite Phenolic Resin Graphite Cement	HEPA Filters Carbon Soot & Filter Bags (Contaminated) Graphite Sodium Chloride (Contaminated)
Recovery	Nitric Acid Process Water	HEPA Filters Silicon Carbide Shards (Contaminated)

Characterization	Hydrochloric Acid Sodium Hydroxide Mercury Silicon Carbide Diamond Grinding fluid Helium	HEPA Filters Process Water (Contaminated) Mercury Contaminated Fuel Particles Organic Waste (oil) (contaminated)
GFR Dispersion Fuel		
Fabrication	Hydrofluoric Acid Magnesium Hydrogen Graphite Polyethylene Glycol Argon Methyltrichlorosilane Silicon Sodium Hydroxide Process Water	HEPA Filters Fluorination Condensate Water Magnesium Fluoride (Contaminated) Sodium Chloride (Contaminated)
Recovery	Nitric Acid Process Water	HEPA Filters SiC Shards (Contaminated)
Characterization	Hydrochloric Acid Sodium Hydroxide Helium Silicon Carbide Diamond Grinding fluid	HEPA Filters Process Water (Contaminated) Organic Waste (oil) (Contaminated)

3. SPENT FUEL TREATMENT FACILITY INTERFACES

3.1 Fuel Fabrication Feed Material Forms

The SFTF Scoping Study[2] currently identifies the U, Pu, Np, Am, and Cm treatment products as oxides. The exact stoichiometry of the oxides is not specified at this time, but the product oxides would need to be sufficiently stable to meet existing transportation and storage regulations. In general, isotope oxide inputs are appropriate for fuel fabrication, although the metal and GFR dispersion fuel processes would be simplified if metal feed could be provided. The remaining processes should work well with oxide inputs but may require stoichiometry adjustments to obtain the needed feed material reactivity for fabrication. For example, mixed oxide fuel fabrication needs a $U_{2.08}$ input form, which is further reduced from the nominal UO_3 expected as the SFTF product. TRISO fuel fabrication can readily use a high surface area UO_3 as input material but would have difficulty with $UO_{2.08}$. Unfortunately, fuel fabrication developer understanding of the effects of oxide stoichiometry is limited at this time as developers have had to use existing stocks of target isotopes in their work, often without the resources that would allow them to study and optimize input stoichiometry.

At this time, no oxide stoichiometry adjustment processes are shown on the flow sheets. The need for such processing is dependent upon the product output flexibility available to the SFTF and the completion of needed fabrication development. This situation is further complicated by the fact that each isotope will respond differently to fabrication processing as a function of its particular oxide stoichiometry. Significant time and effort may be involved in finalizing the fuel fabrication feed material needs and matching them with acceptable SFTF product outputs. Further development of communication links and interfaces between the Separations Work Group and the Fuel Development Working Group in FY-05 should assist in this endeavor.

3.2 Scrap Recycle Support Considerations

Some fuel scrap that is generated during fuel manufacturing can be recovered with standard recovery techniques and recycled back into the fuel process. The standard recovery techniques identified on the process flow sheets are effective for individual isotopes, but their effectiveness and usefulness for recovering a blend of isotopes is currently unknown. Some portion of the scrap that is generated may need isotope separation to make the material recyclable back into the fuel process. In these situations, returning the scrap to the SFTF for separations processing may be the only option other than dispositioning the material as a waste for burial.

The feasibility and limitations for sending scrap materials back to the SFTF for reprocessing need to be determined and the interface requirements for such return material need to be worked out. Scrap return assumptions would also have an impact on the required sizing of the SFTF unit processes and, potentially, the facility size.

Another interface requirement relative to scrap recycle with the SFTF is the listing of elements or compounds that are incompatible with SFTF processes and cannot be allowed in any scrap recycle stream. This information may allow adjustments to the process flow sheets that preclude the introduction of prohibited materials into the fuel processes and ensure that they do not poison scrap returns that could otherwise be handled at the SFTF.

4. TECHNICAL CHALLENGES FOR AFCI FUEL PROCESSES

The very isotopes that are expected to make AFCI transmutation fuels undesirable for would-be terrorists or proliferants will increase the complexity and expense of fuel fabrication. The fabrication complexity comes from:

- The need for remote processing, QC, Nuclear Materials Control and Accountability (NMCA), and in-process storage
- Processing multiple isotope fuels where the properties of each isotope are different
- Maintainability of the fuel process, QC, NMCA, and storage functions.

4.1 Remote Processing, QC, NMCA, and Storage

The isotopic makeup of the fuel feed material will include the alpha contamination issues from Pu and Np, the gamma radiation issues from Am, and most probably the spontaneous fission and neutron radiation issues of Cm. Although very small quantities of these materials may be feasible to handle in gloveboxes, larger quantity fabrication is expected to take the processing operations outside the realm of radiological safety for anything other than some level of remote fabrication. Analyses to determine the extent of required operator protection as a function of material throughput need to be performed early in the program to provide a solid planning base for the future FFF. If hot cell fabrication techniques are required, it would dictate the need to simplify fabrication processes and QC testing sequences to the extent possible to minimize cost and maximize feasibility.

Historically, fuel fabrication was performed as a series of batch operations with the batch placed in a storage/hold location while quality control tests provided verification that the unit processes performed on the material were successful and the batch was acceptable for further processing. Although somewhat inefficient, the batch processing approach was well suited for processing LWR fuel under Nuclear Regulatory Commission (NRC) regulations with nuclear industry QC. NMCA functions were facilitated with the batch processing approach as individual lots could be readily weighed, inventoried, and tied to QC data sets to obtain nuclear material mass balances on a regular basis.

A number of issues may challenge the logic of performing remote batch processing of transmutation fuels:

- The isotopic content of the fuels would require specially designed in-process storage containers (critically safe) and may severely limit the batch sizes. This would increase the required size of interim storage vaults and increase the amount of QC testing required,
- QC sampling and testing, as well as all sample management and control functions, would need to be performed remotely. (Some tests on very small quantities of material may be allowed within a glovebox).
- Batch weighing and recording for NMCA would all be remote.
- The movement and handling of batches and batch samples to and from processing stations would significantly add to the complexity of the hot cell operations.

A continuous processing approach to fuel fabrication within the hot cell may need to be considered as an improvement over batch processing. Continuous processing would minimize the material movements required within the processing cell environment, minimize the size requirements of the processing cells; and limit storage to incoming feed materials, finished products, and scrap recycle. Continuous processing would require QC and NMCA functions to be automated, but the effort to automate these functions may be less costly overall than setting them up and operating them as remote manual operations.

4.2 Multi-Isotope Fuels

Traditional LWR fuel plants process a single element (uranium) to a consistent sintered oxide form as pellets for irradiation. Commercial MOX fuel plants have added to the complexity of fuel manufacture by adding Pu. The preliminary process flow diagrams provided in this document assume that a number of isotope oxide products coming from the SFTF can be mixed together and processed like a single material. However, with up to five elements involved (U, Pu, Np, Am, and Cm), AFCI transmutation fuel manufacture may not be so straightforward. Each element involved in the unit processes adds to the complexity of the chemical system and may narrow the acceptable processing space. Also, because of their radioactivity and limited commercial use, much less is known about the properties of some of these isotopes or their interactions in specific chemical combinations. Current development efforts have already revealed significant processing issues with Am. Fuel development involving significant quantities of Cm has not yet been attempted.

4.3 Maintainability of Fuel Fabrication Operations

The existing commercial fuel manufacturing industry has not had to deal with the issues of remote maintenance of processing equipment. The specific restrictions for hands-on maintenance of transmutation process equipment are still unknown, but are expected to be significant. Although many of the lessons learned from maintaining irradiated fuel reprocessing equipment would be applicable to the maintainability of transmutation fuel manufacturing equipment, new challenges are expected.

5. SUMMARY RECOMMENDATIONS

5.1 Process Flow Diagrams

The following future work should be performed relative to process flow diagrams for transmutation fuel processes:

1. The feasibility of scrap recycle using a mixture of isotopes in the forms expected from fuel manufacture should be analyzed and tested.

2. Fuel developers should evaluate and provide any additional stoichiometric limitations information available on feed materials to be used in their processes.

3. Fabrication process, scrap recovery, and characterization flow diagrams should be re-checked for completeness and errors.

4. Mass flows for the processes should be generated for the fuel compositions and throughputs expected for an FFF.

5.2 Spent Fuel Treatment Interfaces

Interface activities between the Separations Working Group and the Fuel Development Working Group should be expanded to cover the following:

1. Determination of the specific product forms expected from the SFTF

2. Flexibility for SFTF to make major adjustments in product forms (e.g., provide metal products)

3. Flexibility for SFTF to provide a variety of stoichiometries for product oxides

4. Capability for SFTF to accept mixtures of isotopes as scrap returns from the FFF

5. Form requirements and limitations for SFTF acceptance of FFF scrap returns

6. Identification of prohibited elements and compounds for FFF scrap return streams.

5.3 Technical Challenges

The following technical challenges identified during the course of this initial work should be pursued to the extent funding permits:

1. Based on mass flow information for the expected FFF and existing isotope radiation emission databases, a set of dose rate calculations should be generated as a function of shielding and process specifics. The dose rate and shielding data should then be compared to Department of Energy (DOE) and NRC radiation exposure guidelines to initially determinate the minimum shielding requirements for a transmutation FFF.

2. Dose rate and shielding data should also be computed for empty but contaminated process equipment and compared to DOE and NRC radiation exposure guidelines to determine the initial requirements for remote maintenance of fuel fabrication equipment.

3. The feasibility of automating process control, NMCA, and QC functions for fuel processes that may be implemented in an FFF should be evaluated.

4. Compatibility analyses and chemistry tests should be performed on the mixtures of isotopes expected to be processed together in an FFF. This work could be integrated with determining the feasibility of performing scrap recovery processes with mixtures of isotopes.

6. REFERENCES

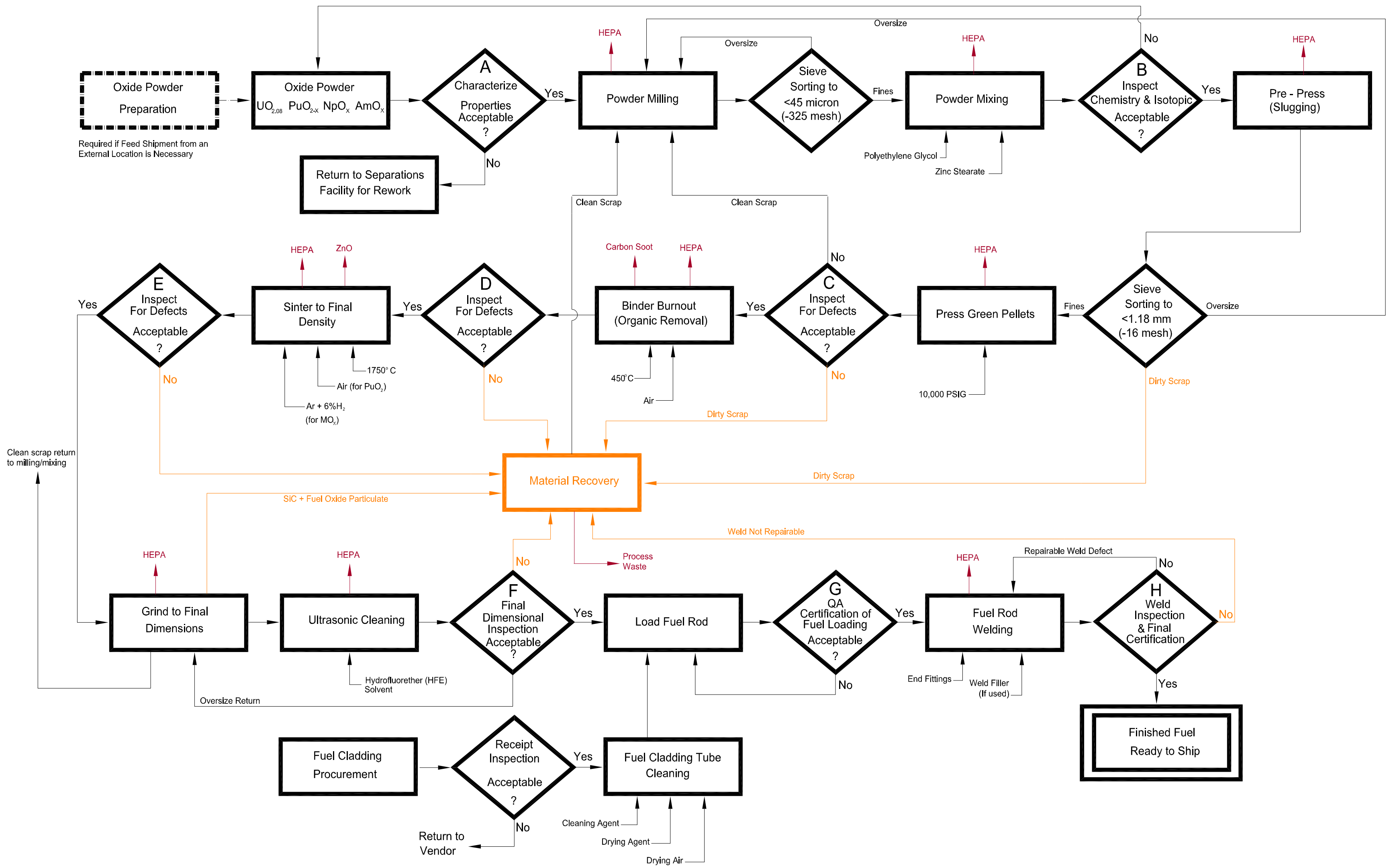
1 *Advanced Fuel Cycle Initiative (AFCI) Program Plan* (Draft), January 30, 2004

2 Washington Group International, *Scoping Study for the Spent Fuel Treatment Facility (3 Volumes)*, Western Operations Center, Denver, CO. Job No. 26861-004, January 2004 (Official Use Only).

Attachment 1

9/9/04 Rev B

Mixed Oxide Fuel Process Flow Diagram



Attachment 2

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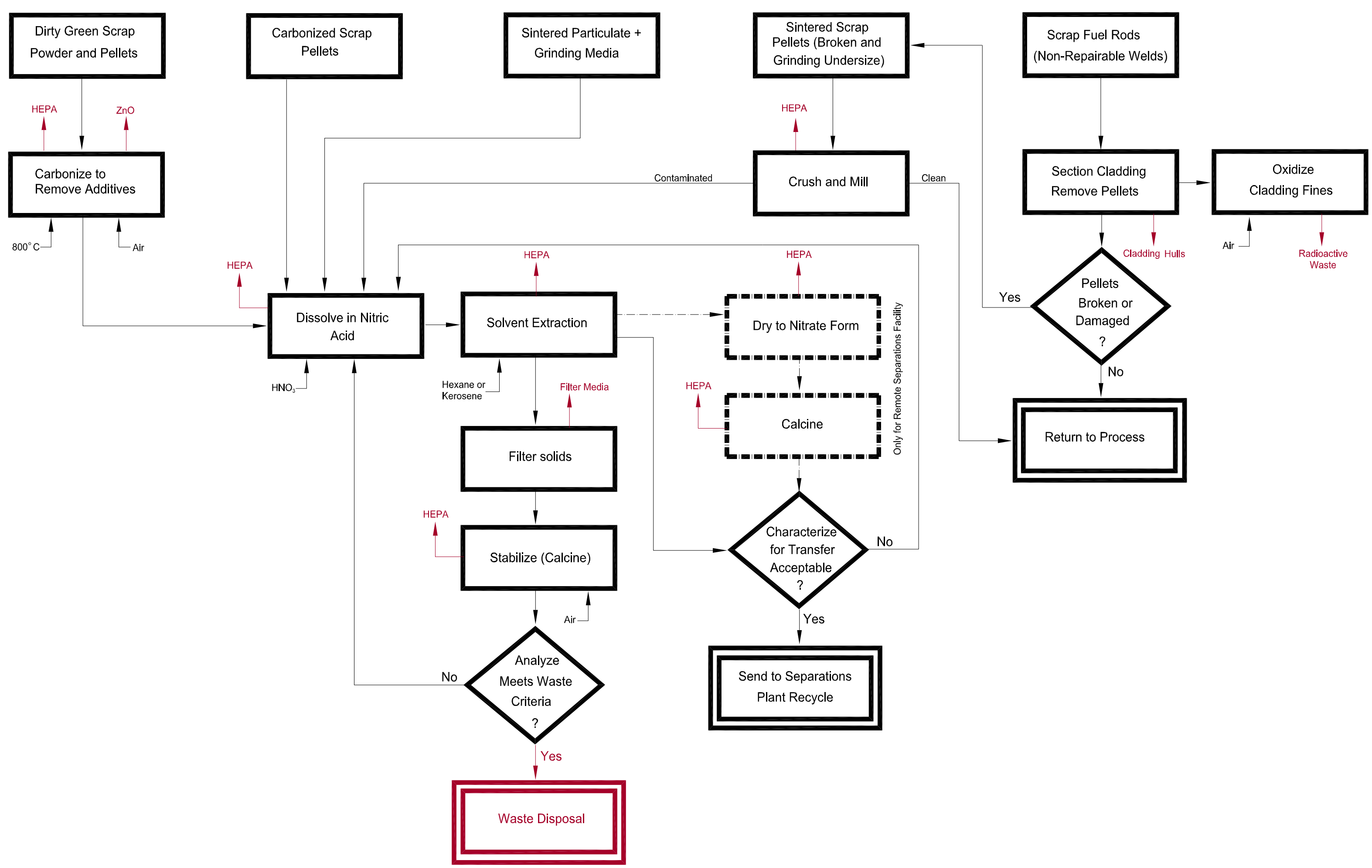
MOX Material Recovery Process Flow Diagram



Attachment 3

Mixed Oxide and Nitride Characterization Process Flow

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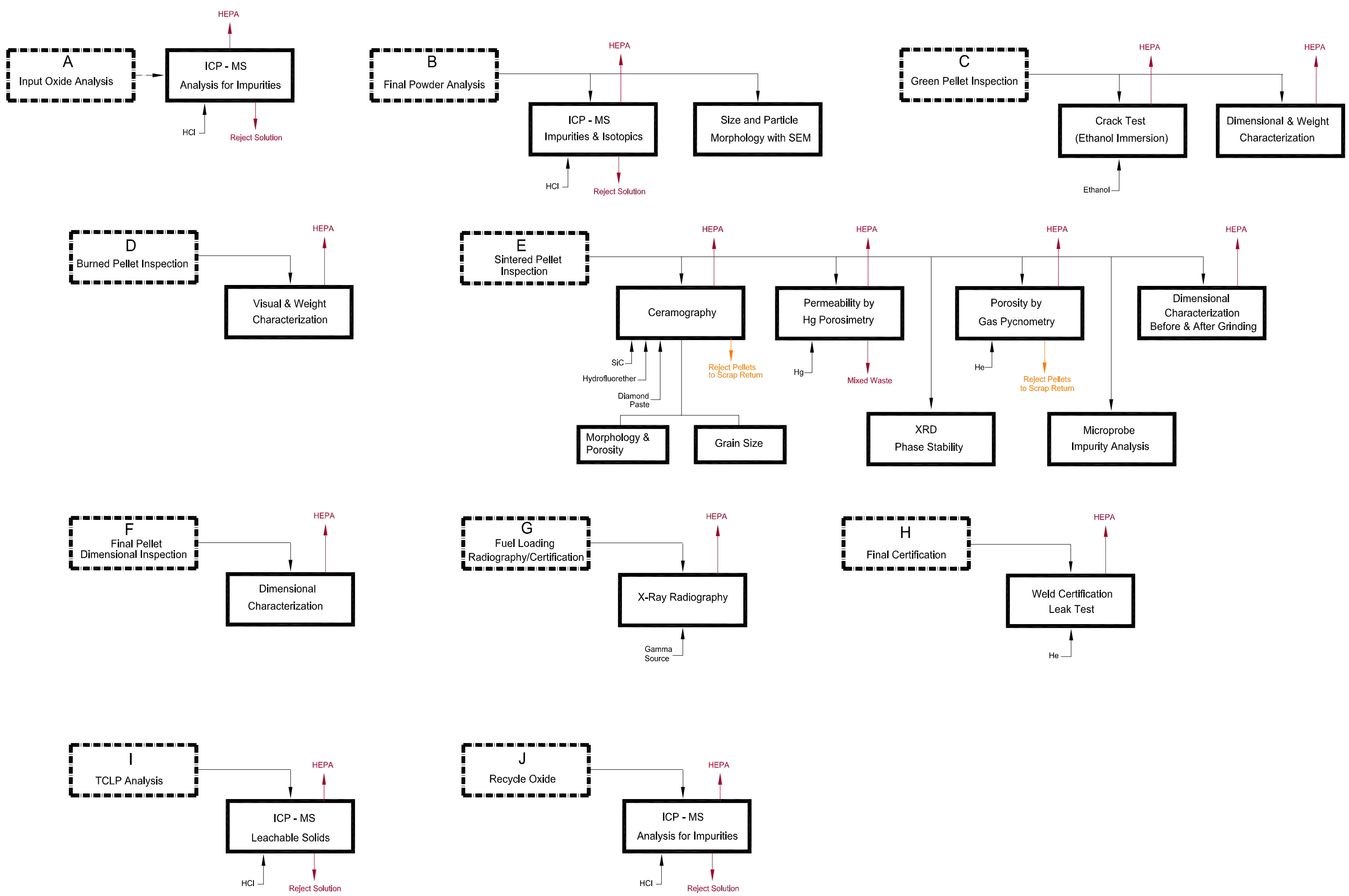
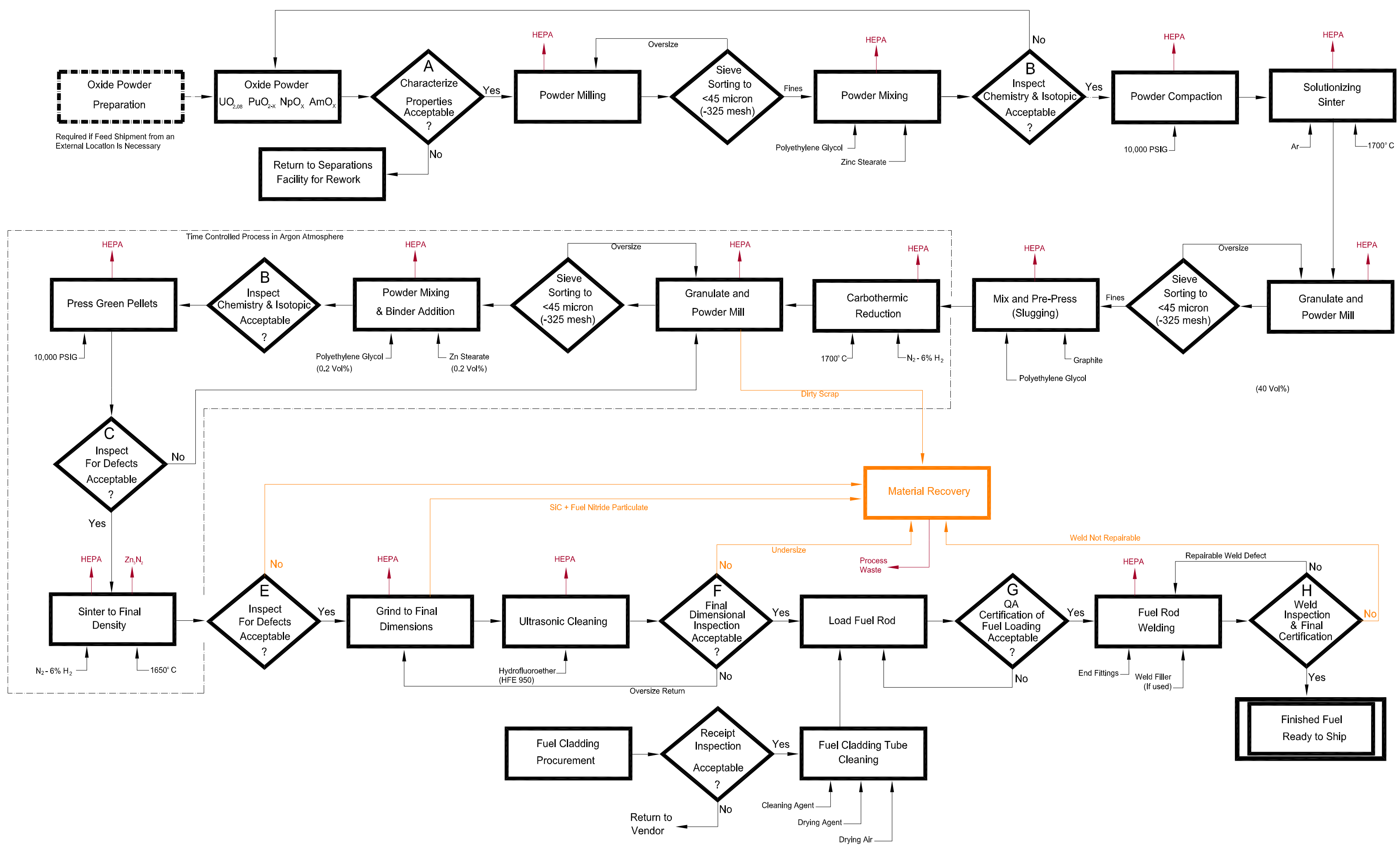


Attachment 4

9/8/04 Rev B

Mixed Nitride Fuel Process Flow Diagram



Attachment 5

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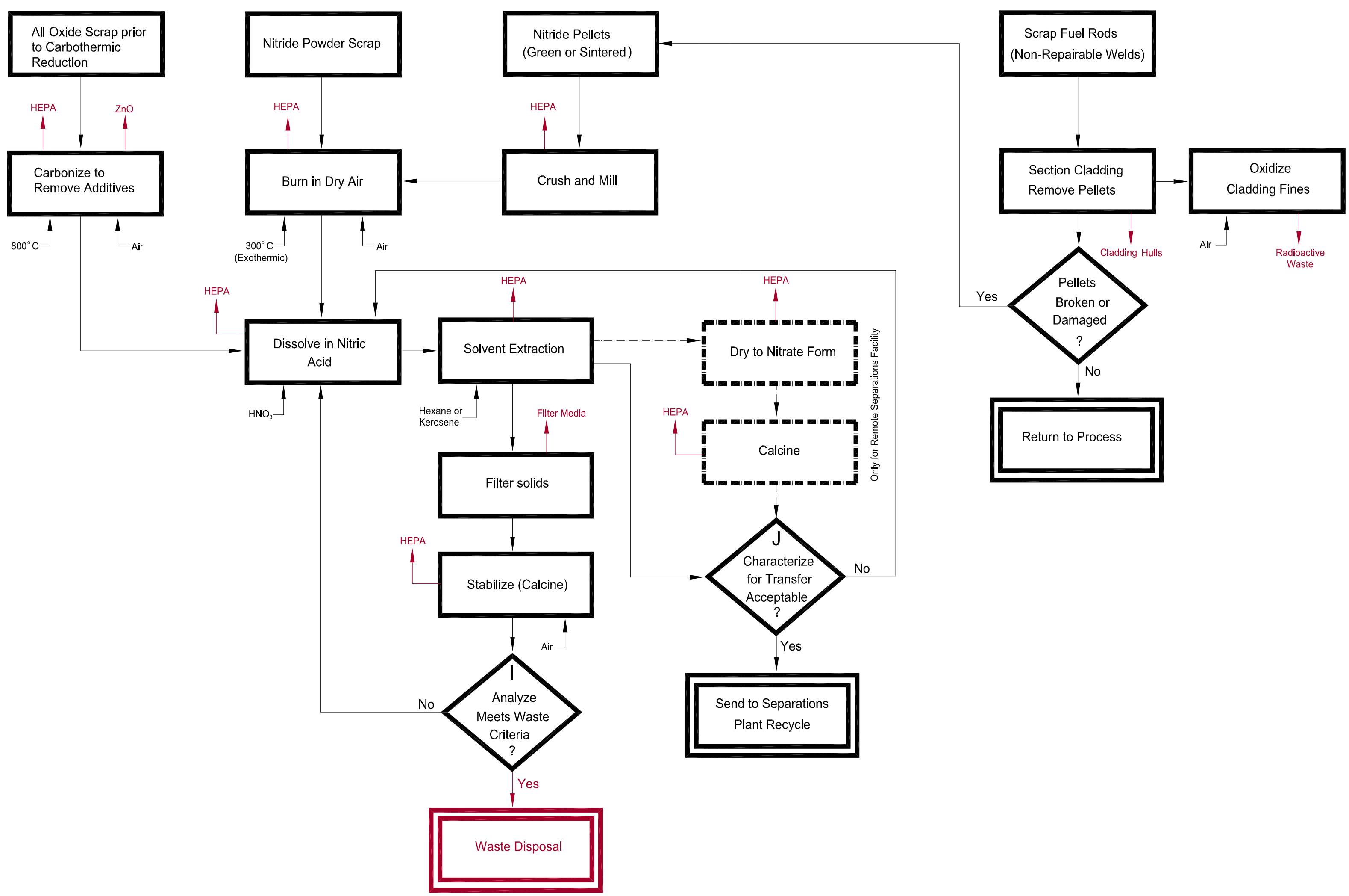
Mixed Nitride Material Recovery Process Flow



Attachment 6

Metallic Transmutation Fuel Process Flow Diagram

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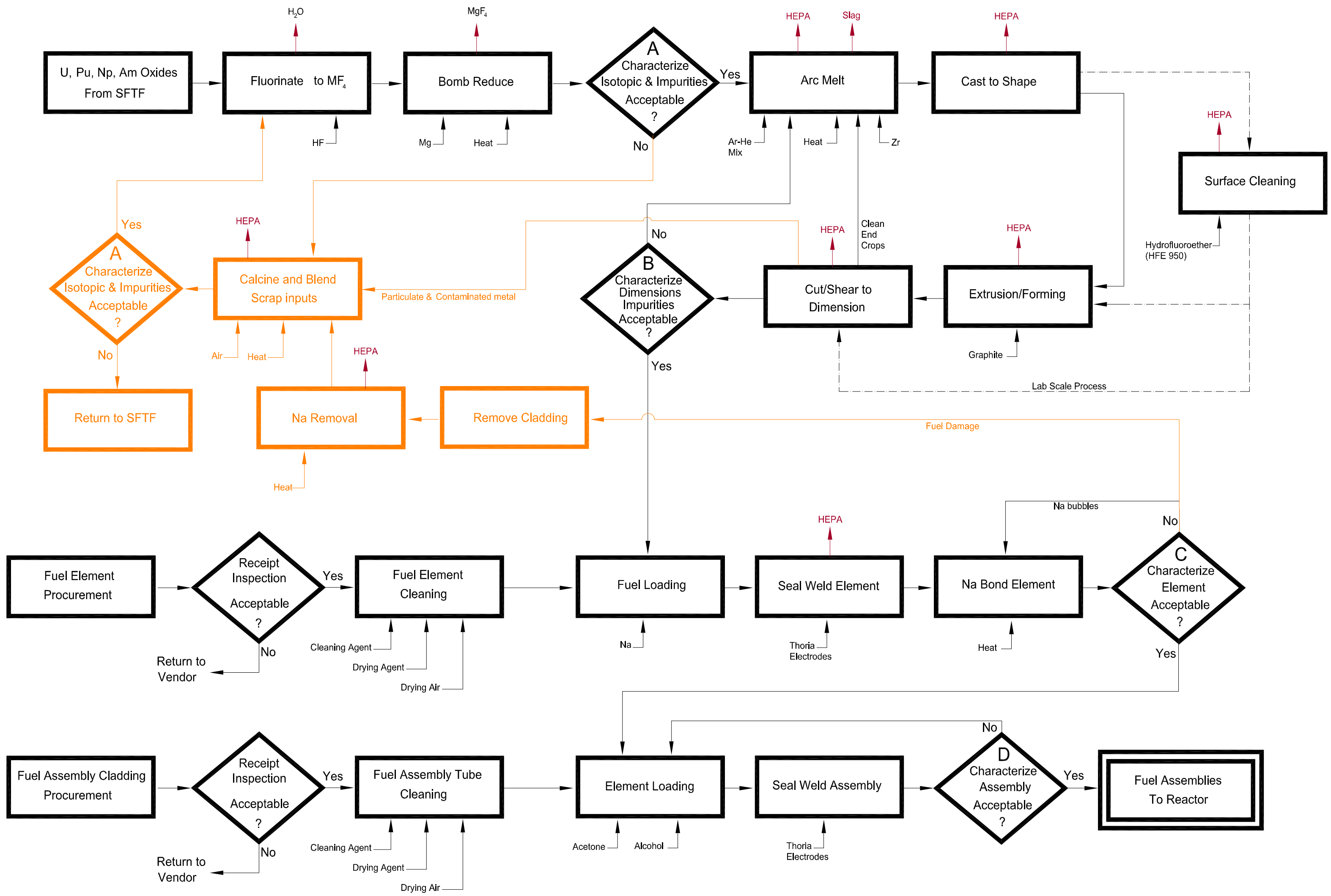

Attachment 7

Metal Fuel Characterization Process Flow

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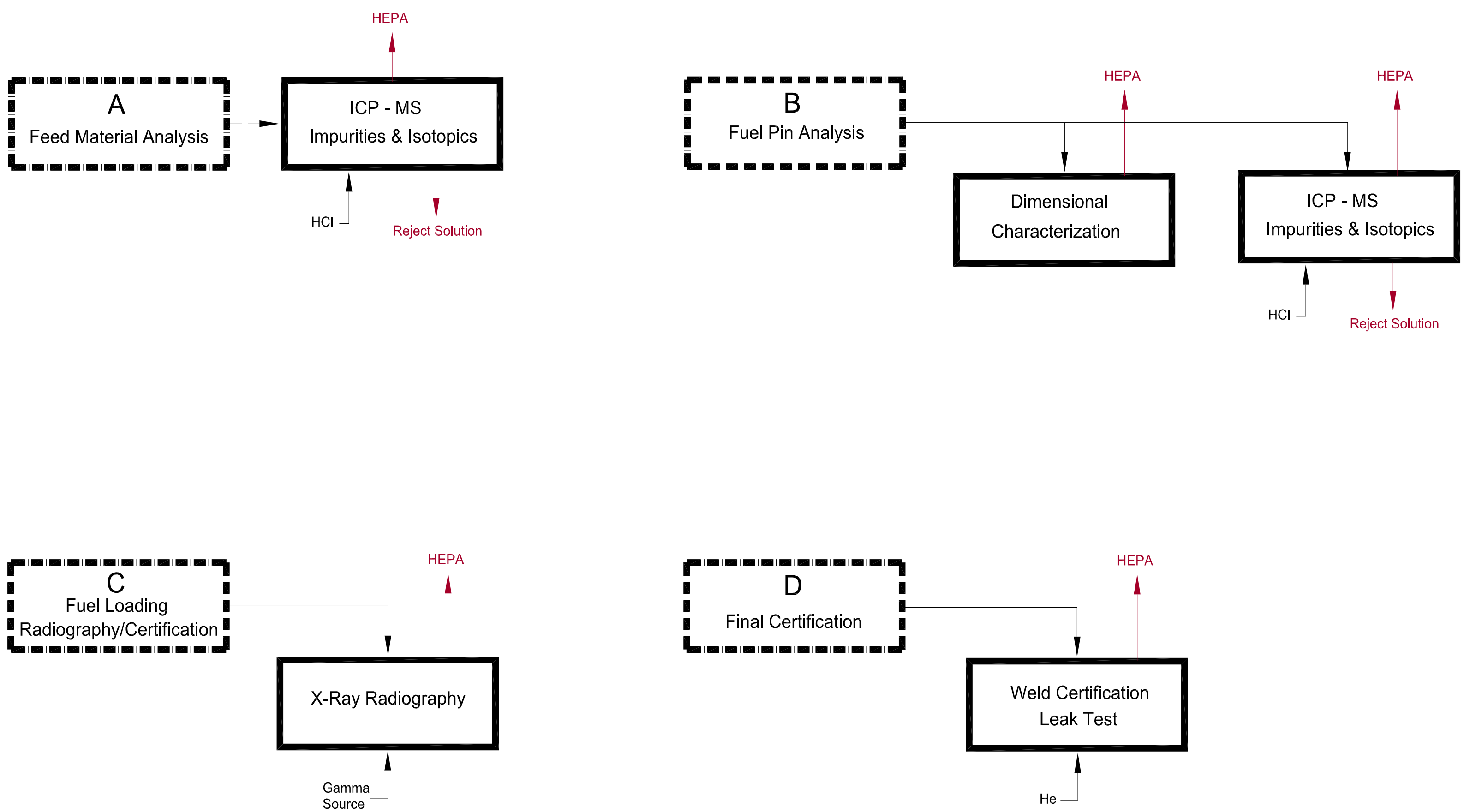

Attachment 8

TRISO MOX Fuel Process Flow Diagram

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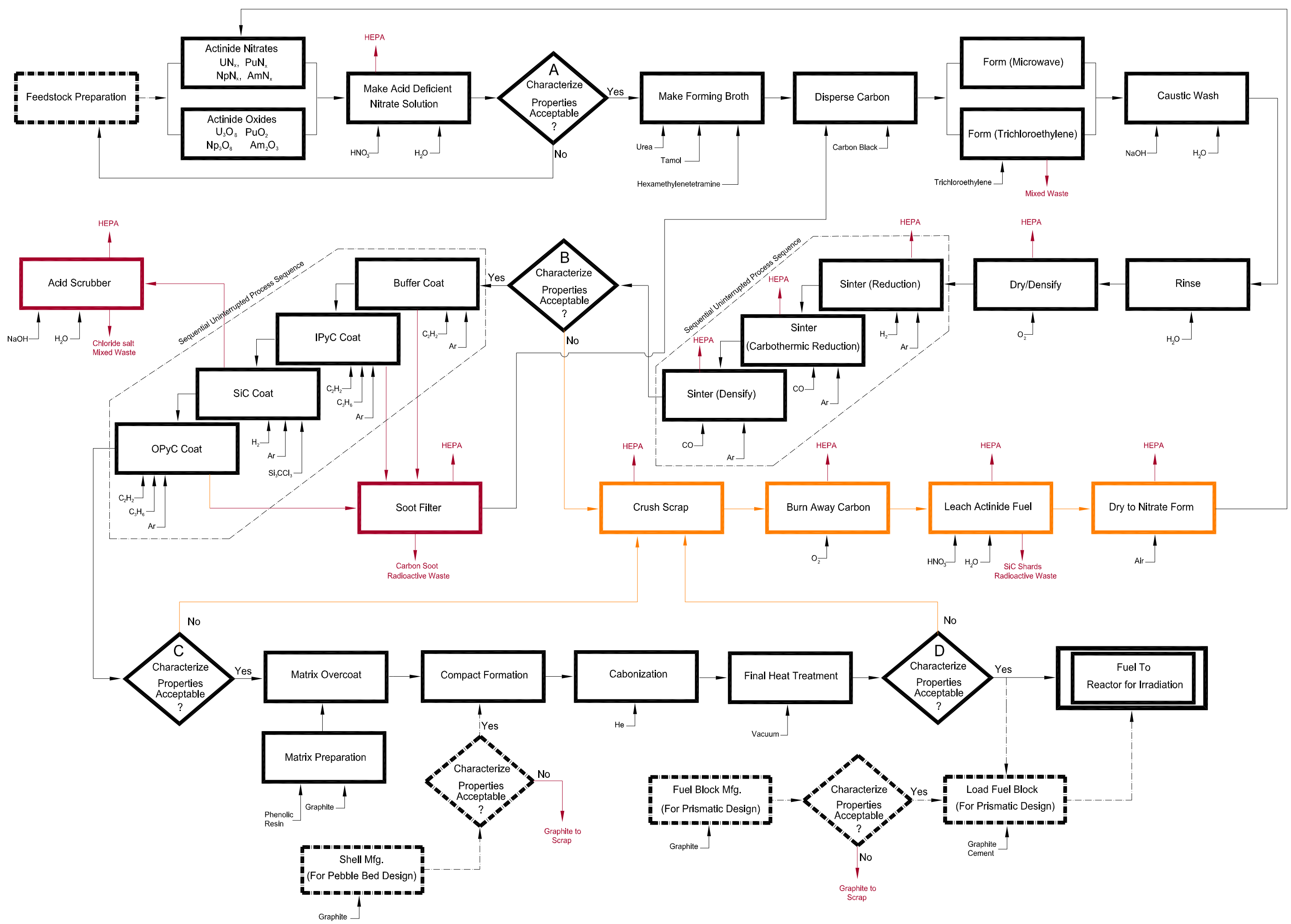

Attachment 9

TRISO MOX Fuel Characterization Processes

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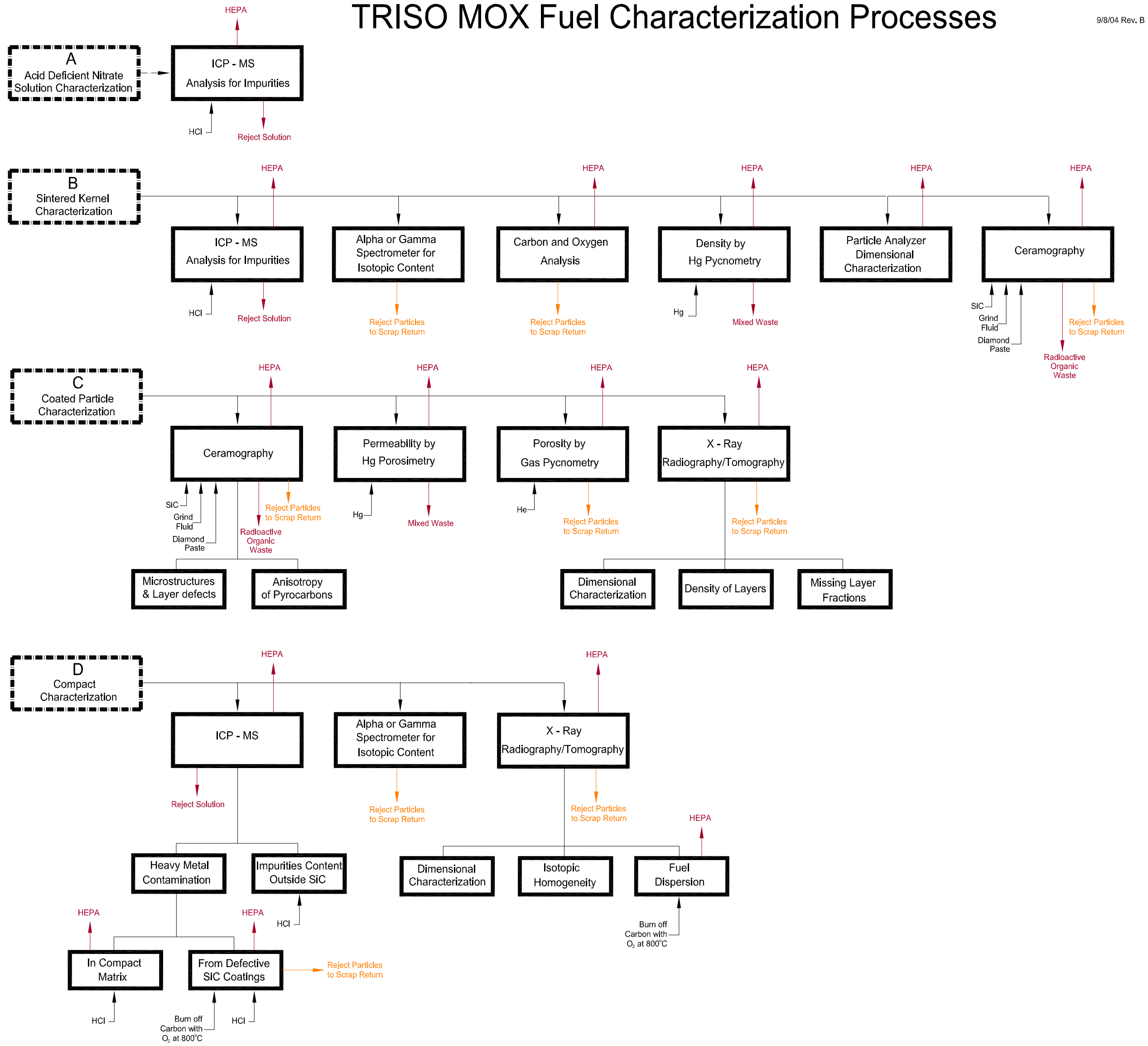

Attachment 10

GFR Dispersion Fuel Process Flow Diagram

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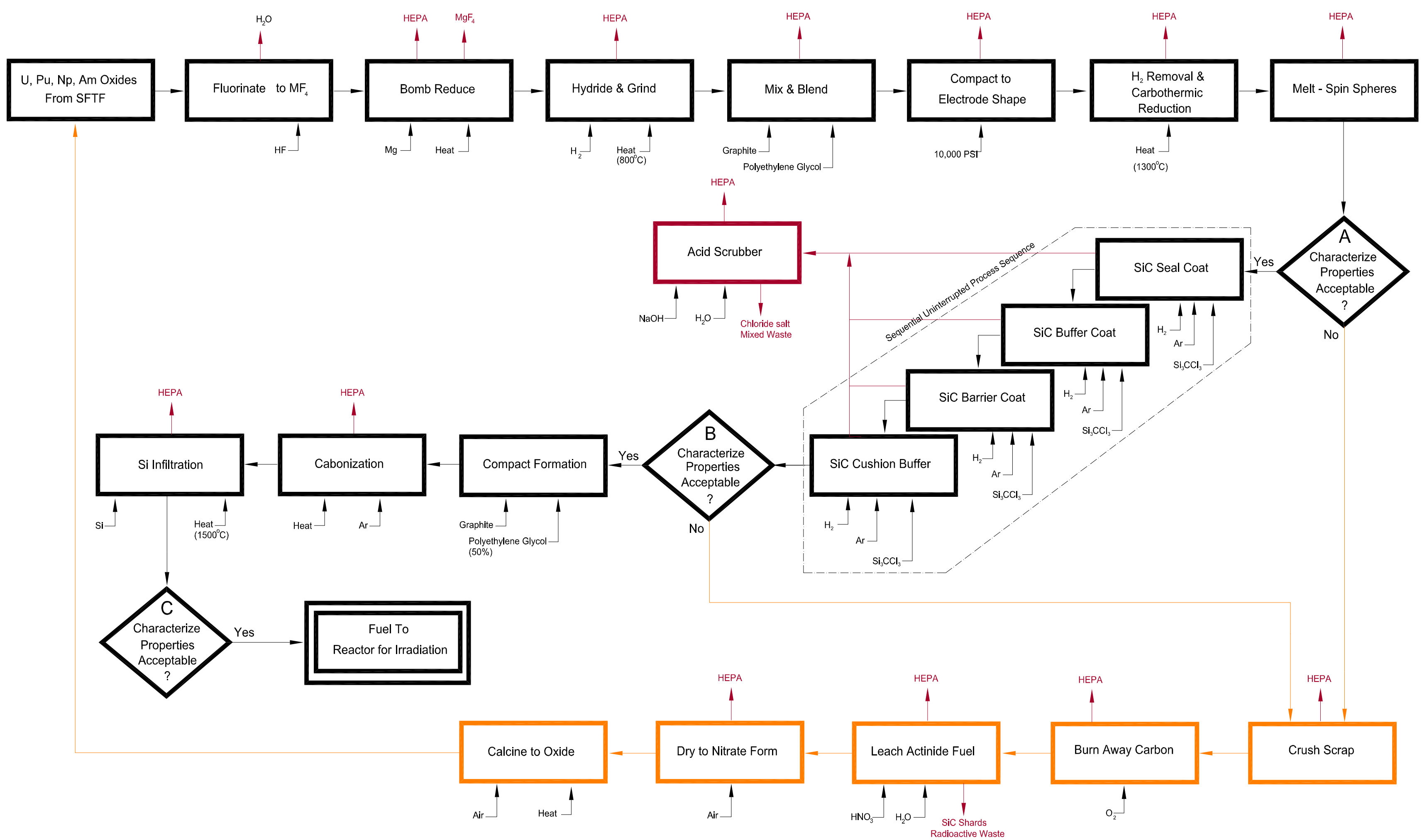

Attachment 11

GFR Fuel Characterization Processes

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